In-situ Blast Testing of Shear-Screw Mechanical Couplers

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Abstract

The purpose of this study is to determine the capability of mechanical splices in reinforced concrete to develop the ultimate strength of typical reinforcement without limiting its ductility, as required by UFC 3-340-02. This study also follows the UFC 3-340-02 requirement for a specific mechanical coupler to be tested in a dynamic application prior to use in blast resistant structures. Mechanical couplers have been developed to meet requirements in conventional design codes, such as ACI, and to meet the demands of cyclic loading in seismic zones, however, little in-situ testing has been conducted on mechanical couplers under high strain rate dynamic load, as would be typical in a blast response.

The 2009 effort included a test series on one-way reinforced concrete slabs using the BakerRisk shock-tube to simulate blast loads from high explosives and industrial explosions. The shock-tube test series included concrete slabs with continuous reinforcement, lap splices, and mechanical splices for comparison purposes. Both types of splices were placed in areas of the slab subjected to the highest flexural demand, as well as in areas of the slab removed from high flexural demand. The results of this study are limited to the test results of one specific mechanical coupler, namely a shear screw coupling sleeve. At the completion of the test series, BakerRisk concluded that the mechanical coupler was able to develop the reinforcement beyond the dynamic yield strength and not limit the ductility of the reinforcement; however, further testing is required to determine if the couple is capable of developing the full ultimate strength of the reinforcement under blast loading.

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1.0 Introduction

Reinforced concrete structures designed to meet explosive threats may consist of robust concrete walls with multiple layers of steel reinforcement. To maintain structural integrity and stability at significant inelastic support rotations, specific attention is required for detailing the tensile, flexural, and shear reinforcement of cast-in-place walls, roof slabs, and component intersections. Of particular importance is the development of reinforcement at wall-to-wall intersections and splicing of reinforcement at cold joints.

Unified Facilities Criteria (UFC) 3-340-02[1] discusses three types of reinforcement splices; lap splices, welded splices, and mechanical splices. Typical design practice is to splice flexural reinforcement with lap splices, as referenced in the American Concrete Institute (ACI) code;[2] this practice has the potential to create a challenging congested steel pattern that would impact the constructability and cost of the design significantly. While welding of reinforcement is to be avoided in the design of blast resistant structures, the UFC allows the use of mechanical splices if the mechanical coupler is capable of developing the ultimate tensile strength of the reinforcement without reducing the ductility of the rebar. In addition, the mechanical coupler must be tested in a dynamic application prior to use in blast resistant structures. As another point of reference, UFC 3-340-01[3] only allows mechanical splices to be used in reinforcement concrete if the structure is designed to respond to the design threat in the elastic realm.

Mechanical couplers have been developed to meet requirements in standard design codes and to meet the demands of cyclic loading in seismic zones, however, little testing has been conducted on mechanical couplers under high strain rate dynamic load, as would be typical in a blast response. A recent study conducted by the U.S. Army Engineer Research and Development Center (ERDC) sought to obtain information regarding the response of mechanical couplers at high strain-rates under uniaxial loading. The ERDC test series tested individual mechanical couplers at various strain rates, using a dynamic loader, with the goal of documenting an off-the-shelf mechanical coupler capable of meeting UFC 3-340-02 requirements, which is similar to the coupler reported in this document.[4,5]

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[1] US Department of Defense, UFC 3-340-02 (TM5-1300), "Structures to Resist the Effects of Accidental Explosions," December 2008.

[2] American Concrete Institute, ACI 318-08, "Building Code Requirements for Structural Concrete and Commentary" 2008

[3] US Department of Defense, UFC 3-340-01 (TM 5-855-01), "Design and Analysis of Hardened Structures to Conventional Weapons Effects," December 2008.

[4] Stephen P. Rowell and Stanley C. Woodson, "High Strain-Rate Testing of Mechanical Couplers," Presented at the 32nd Explosives Safety Seminar, 2008.

[5] Stephen P. Rowell, Clifford E. Grey, Stanley C. Woodson, and Kevin P. Hager, "High Strain-Rate Testing of Mechanical Couplers," US Army Corps of Engineers, Engineering Research and Development Center, ERDC TR-09-8, September 2009.

The test series included six simply supported reinforced concrete slabs; two slabs consisting of continuous reinforcement, two slabs consisting of lap spliced reinforcement and two slabs consisting of mechanical spliced reinforcement. In order to understand and document the behavior of the splices at different stress regions of the slab, splices were located at the mid-span of the slab for one test set and at the top third-span of the span for the second test set. The response of the mechanical splice was monitored by tracking the strain at key points along the reinforcement. Peak midspan slab deflections were captured using high-speed cameras.

2.0 Slab Design

The test-specimen slab design consisted of No. 5 bars spaced at 11 1/4 inches on center spanning in the vertical direction and No. 4 bars spaced at 12 inches on center spanning in the horizontal direction. The overall dimensions of the slab were 8 ft 6 in high by 8 ft wide and a thickness of 5.5 inches. The slab was supported at the top and bottom with simple supports.

Mechanical Splice Design

The reinforcement of two of slabs is spliced with a specific mechanical coupler. As discussed in the ACI, "a full mechanical splice shall develop in tension or compression, as required, at least $1.25f_y$ of the bar" (ACI 318-08, 12.14.3). The ACI requirement for mechanical splice tensile development of $1.25f_y$ (= 75,000 psi) does not meet the UFC requirement for tensile development of f_{du} (= 90,000 psi for A615 steel) therefore a mechanical coupling device that exceeded the ACI requirements was a criteria in selecting an off-the-shelf mechanical splice coupler. The study reported here focused on evaluating one mechanical coupler system, the selection of the shear screw coupler was made due to the ease of installation and availability.

There are multiple suppliers of shear screw couplers; for this study, the Double Barrel Zap Screwlok system by *Barsplice Products Inc*. was selected. The Double Barrel Zap Screwlok is capable of developing 125 percent of the yield strength of a No. 5 bar and has the capacity to develop 150 percent of the yield strength of Grade 60 reinforcement ($1.5f_y$ = 90,000 psi), which exceeds the ACI requirements for mechanical couplers. The Screwlok system is compatible with ASTM A615, ASTM A706 and ASTM A996 reinforcing bars. The double barrel system provides one sleeve for each of the two bars being spliced. By providing two sleeves, the double barrel system is more compact in length than other mechanical couplers. For installation, the rebar slides into the open sleeve of the coupler device, and when the specified torque is applied, a series of cone-pointed interlocking screws forces the rebar deformations to interact with the coupler. The interlocking screws also penetrate the rebar surface for additional mechanical resistance, via dowel action. A photograph of the Double Barrel Zap Screwlok couple is provided in Figure 1 . For the development of a No. 5 bar, 3 cone-pointed interlocking screws are provided at each bar location. An average torque of 50 ft-lbs was applied to each interlocking screw in order to develop the full mechanical resistance of the coupler, as prescribed by the coupler manufacturer.

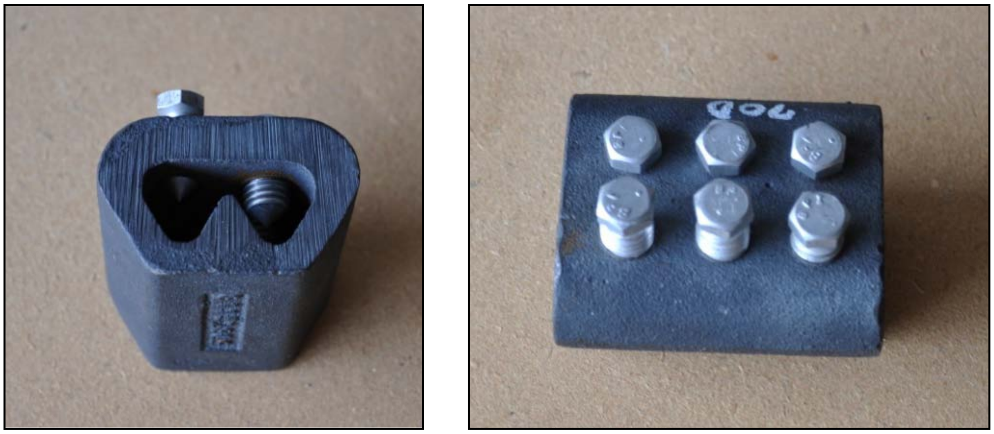


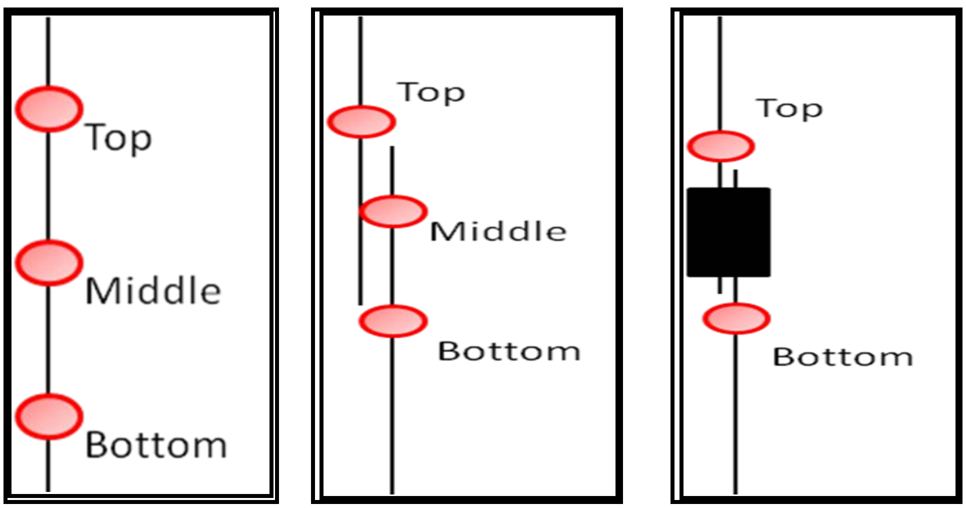
Figure 1. Double Barrel Zap Screwlok

3.0 Test Series

Dynamic testing of the reinforced concrete slabs was conducted at the BakerRisk test facility utilizing an air-driven shock tube. A photograph of the shock tube as configured for the test series is shown in Figure 2. Data gathering equipment utilized in this test series included; dynamic pressure measurement, dynamic reaction measurement, strain measurement, high-speed video, normal video, and still photography.

Figure 2. BakerRisk Shock Tube

Locations for strain gauges were selected based on critical areas of a splice or areas of high strain along the reinforcement. Eight strain gauges were utilized for each test. All strain gauges were Tokyo Sokki Kenkyujo gauge products (model number FLA-5-11-5LT) and were arranged along the rebar to collect information at both ends of the splice or splice location. For slabs with continuous reinforcement, strain gauges were placed in the same locations as the lap splice slabs. Gauges were placed above the splice location (Top), at the middle of the splice location (Middle, for continuous and lap slabs only), and below the splice location (Bottom). The strain configuration used for the test series is shown in Figure 3; red highlight denotes a strain gauge location on the bar. Table 1 provides the location of the eight strain gauges for each test.



Continuous *Lap Splice* *Mechanical Splice*

Figure 3. Strain Gauge Layout

Table 1. Strain Gauge Locations

Test No.	Bar 1	Bar 2	Bar 3	Bar 4
1	Top, Middle, Bottom	Top, Middle, Bottom	Top, Bottom	N/A
2	Top, Middle, Bottom	Top, Middle, Bottom	Top, Bottom	N/A
3	Top, Bottom	Top, Bottom	Top, Bottom	Top, Bottom
4	Top, Bottom	Top, Bottom	Top, Bottom	Top, Bottom
5	Top, Bottom	Top, Middle, Bottom	Top, Middle, Bottom	N/A
6	Top, Middle, Bottom	Top, Bottom	Top, Middle, Bottom	N/A

3.1 Test Results

A total of six shock tube tests were conducted. The test results demonstrated that the reinforced concrete slabs with traditional lab splices and mechanical splices have a similar global response (peak deflection) to the reinforced concrete slabs with continuous reinforcement. Figure 4 provides a comparison of the pressure histories for Test 1 and Test 6. Note the blast load for Test 4, 5, and 6 was higher than the blast load used for Test 1, 2, and 3 in order to observe the behavior of the slabs at a higher response range. The applied blast loads and slab responses are provided in Table 2.

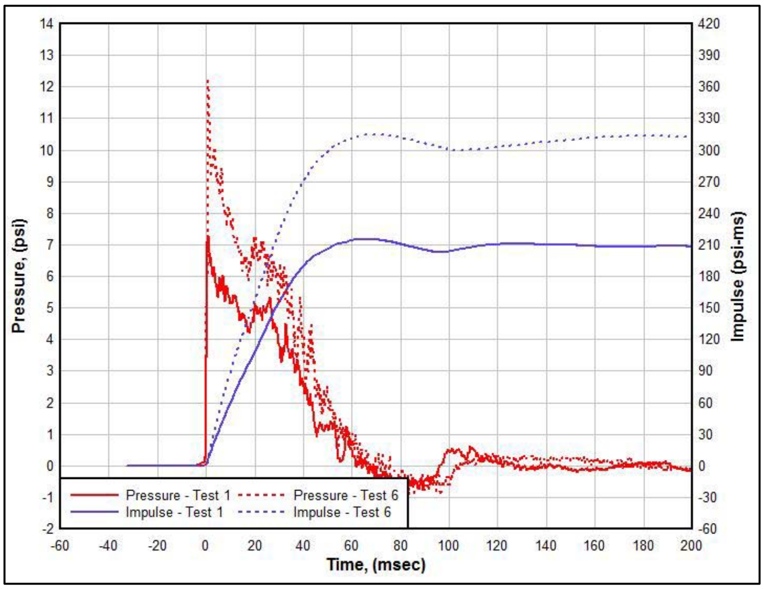


Figure 4. Comparison of Pressure-Time History

Table 2. Overview of Test Results

Test Set	Test No.	Specimen Reinforcement Description	Applied Pressure (psi)	Applied Impulse (psi-ms)	Peak Measured Deflection (in)
1	1	continuous reinforcement	7.7	217	2.3
	2	lap splices at mid-span	7.6	213	2.3
	3	mechanical splices at mid-span	7.9	221	2.0
2	4	mechanical splices at third-span	10.7	306	5.5
	5	lap splices at third-span	10.8	311	5.8
	6	continuous reinforcement	10.6	297	6.0

Peak strain gauge readings for each test are provided in Table 3. The strain gauge readings demonstrate that the spliced rebar, both traditional and mechanical, was able to develop strains that exceed the dynamic elastic strain of 60 ksi steel (77,200 psi / 29,000,000 psi = 0.0027). In addition, the data demonstrates that the peak strains reached by the spliced rebar are comparable to the peak strains reached by the continuous rebar. Strains that exceed the dynamic elastic strain of the rebar are shown in **bold**. For gauges that provided no reading or irrelevant data, 'n/a' is shown in the table.

Table 3. Peak Strain Measurements

Test No.	Strain Gauge Reading							
	Strain Gauge Number							
	1	2	3	4	5	6	7	8
1	**0.0126**	0.0024	**0.0089**	n/a	**0.0128**	**0.0036**	**0.0158**	**0.0076**
2	**0.0173**	0.0016	**0.0067**	**0.0037**	**0.0033**	**0.0126**	**0.0174**	**0.0147**
3	**0.0029**	**0.0130**	**0.0124**	**0.0155**	**0.0129**	**0.0106**	**0.0129**	**0.0138**
4	**0.0032**	**0.0030**	n/a	n/a	n/a	n/a	**0.0060**	**0.0205**
5	0.0010	**0.0231**	n/a	**0.0128**	**0.0147**	0.0024	**0.0054**	**0.0678**
6	0.0018	**0.0270**	0.0021	**0.0220**	**0.0068**	0.0009	**0.0080**	**0.0302**

Figure 5 provides a comparison of the average strain histories from a Test 1, 2 and 3. Note, in calculating the average strain histories, the center gauges from Test 1 and 2 were excluded. Figure 6 provides a comparison of the average strain histories from the bottom strain gauge in Test 4, 5 and 6.

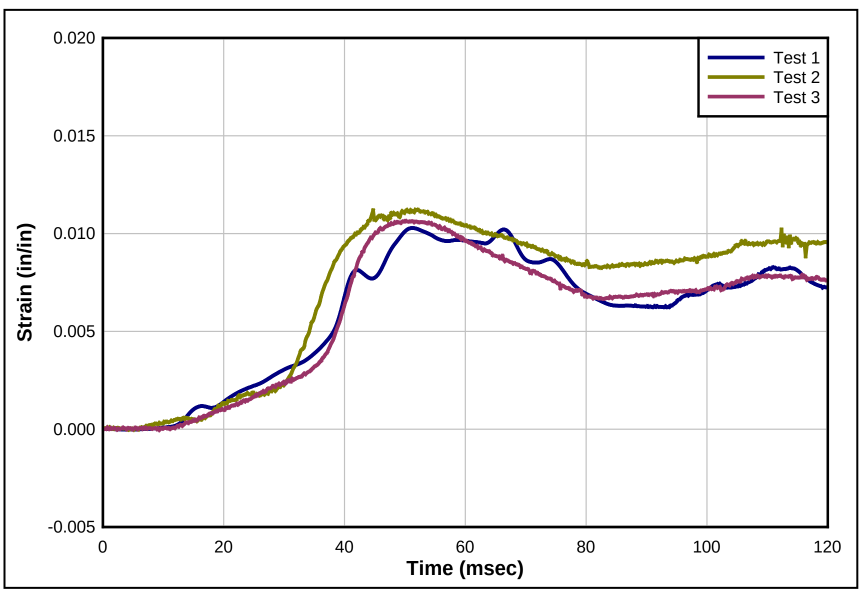


Figure 5. Comparison of Average Strain Histories – Test 1, 2, 3

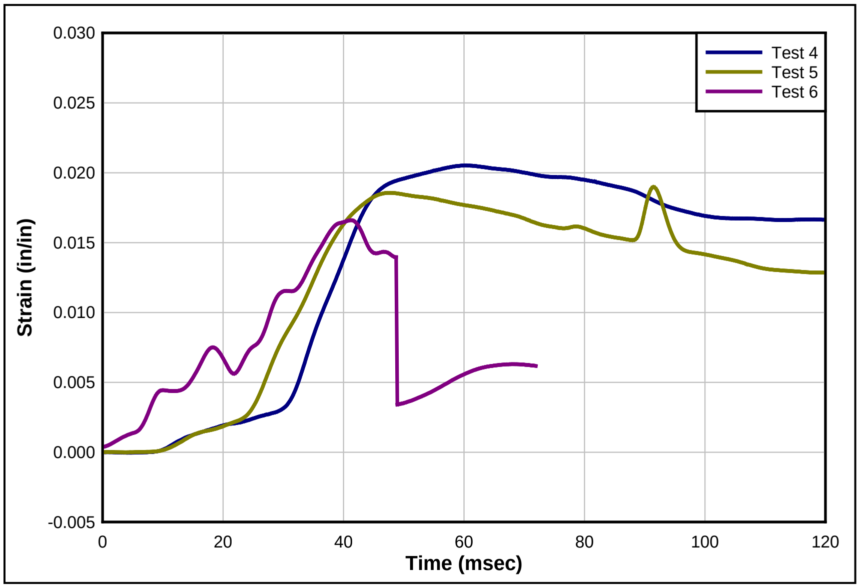


Figure 6. Comparison of Average Strain Histories – Test 4, 5, 6

3.2 Post Test Analysis

The performance of the mechanical splices can be quantified by comparing the strain gauge readings for the continuous reinforcement case and the strain gauges for the mechanical splice case. The Test 1 strain gauge results for Bar No.1 are compared with the Test 3 strain gauge results for Bar No. 1 in Figure 7.

For Test 1, the slab with continuous reinforcement, the peak measured strains were 0.0126 (located 12 inches above the bar center) and 0.0089 (12 inches below the bar center). For Test 3, a slab with mechanical splices at mid span of the slab, the peak strain measured above the splice was 0.0029 and a peak strain of 0.0173 was measured below the mechanical splice. The reinforcement on both sides of the mechanical splice exceeds the dynamic yield strain of Grade 60 reinforcement. The data leads to the conclusion that the mechanical splice was able to develop the dynamic yield strength of the reinforcement and was able to develop strains equal to or greater than those measured in the continuous reinforcement.

Figure 7 also provides a comparison of the yield point for the reinforcement in Test 1 and the yield point for the reinforcement in Test 3. The strain data concludes the yield point of the reinforcement was not negatively impacted by the mechanical splice.

Section 4-21.8 of UFC 3-340-02 allows for mechanical couplers to be used to splice reinforcement if the coupler is capable of developing the ultimate tensile strength of the reinforcement without limiting the ductility. The yield point for the spliced reinforcement occurred at a strain that is approximately equal to the dynamic yield strain of Grade 60 reinforcement. In addition, the mechanical splice was able to develop strains seven times greater than yield.

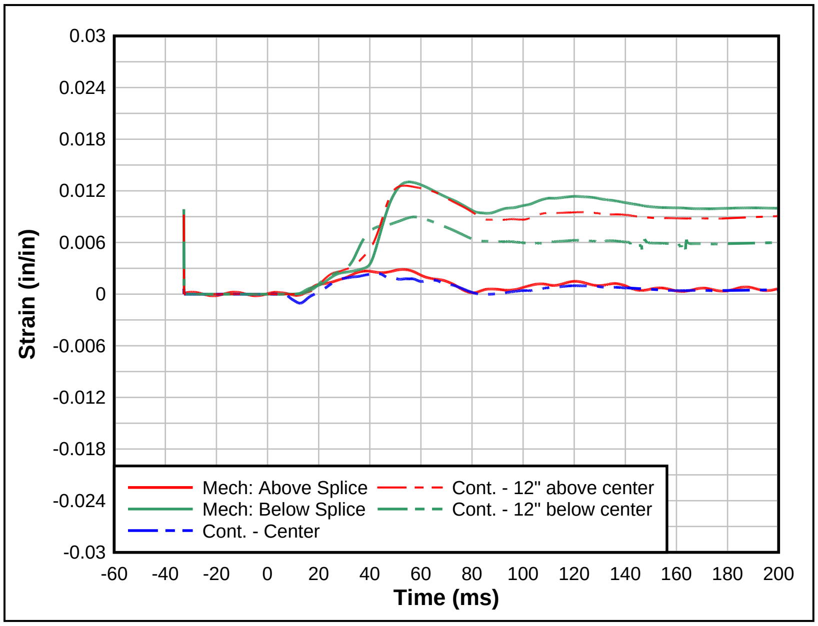


Figure 7. Bar 1 Strain Comparisons from Test 1 and Test 3

The Test 1 strain gauge results were also compared with Test 3 strain gauge results for a bar located at the center of the slab, as shown in Figure 8. For Test 1, the peak strain was measured at the center of the bar (0.0128). For Test 3 the peak strain was measured above the splice (0.0129). The data leads to the same conclusion as before; the mechanical splice was able to develop the dynamic yield stress of the reinforcement and was able to develop strains equal to those measured in the continuous reinforcement.

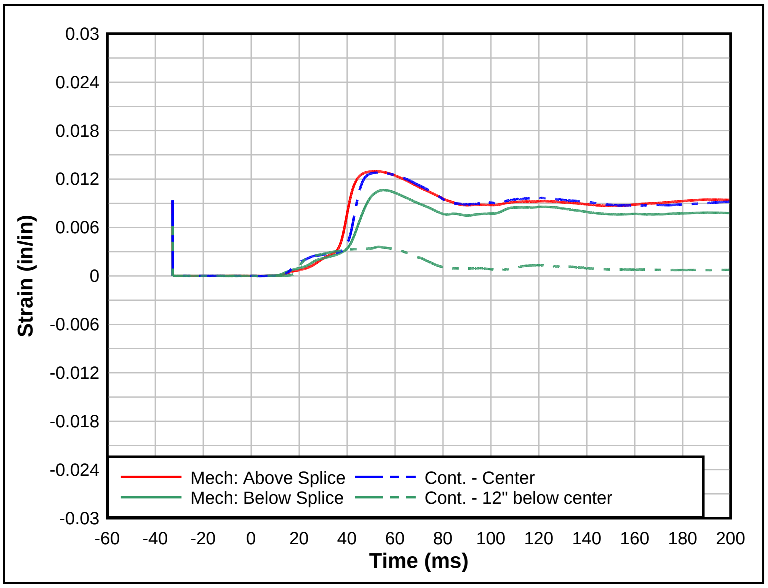


Figure 8. Center Bar Strain Comparisons from Test 1 and Test 3

A comparison of the peak strain readings was made for the Test 4 strain gauge results and the Test 6 strain gauge results. The graphical comparison for the bar located near the right edge of the slab is provided in Figure 9. The strain gauges for Test 4 and Test 6 were placed outside of the critical moment region of the slab, however, the blast load applied to the concrete slab in Test 4 and Test 6 was higher than the blast load applied to the slab in Test 1 and Test 3. For Test 4, mechanical splices at the top third span, the peak strain was measured below the splice location (0.0205). The gauge above the splice location showed a yield strain equal to 0.0028.

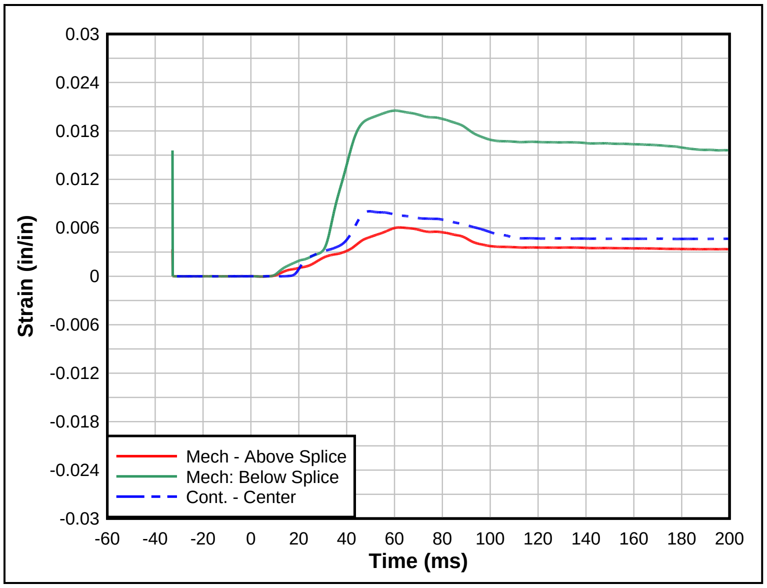


Figure 9. Edge Bar Strain Comparisons from Test 4 and Test 6

Comparing the results from the continuous reinforcement and spliced reinforcement test leads to the conclusion that mechanical splices were able to behave in a similar manner to continuous reinforcement under dynamic load. Test results showed that the mechanical splice was able to develop the full dynamic yield strength of the reinforcing steel and the ductility of the reinforcement was not limited due to the mechanical couple.

4.0 Conclusions

After completing the test series and the post-test analysis, the following conclusions were made:

- The splicing of steel reinforcement with traditional lap splices or with the shear screw coupler mechanical splices did not impact the global non-linear response of the reinforced concrete slabs when loaded with dynamic shock loads at significant support rotations.
- The shear screw couplers tested in this program are capable of developing the dynamic yield strength of the reinforcing steel. Section 4-21.8 of UFC 3-340-02 allows for mechanical couplers to be used to splice reinforcement if the coupler is capable of developing the ultimate tensile strength of the reinforcement without limiting the ductility. The test series concluded that the mechanical couple was able to develop the dynamic yield strength of the reinforcement; however, further testing would be required to determine if the coupler is capable of developing the full ultimate strength of the reinforcement under dynamic loading.

- The shear screw couplers tested in this program were capable of developing strains up to eight times the dynamic yield strain of Grade 60 reinforcement. The mechanical splice did not have an impact on the ductility of the reinforcement bars out to this strain level.
- Placing the reinforcement splices away from the peak moment regions of the slab is always a good practice and is recommended, however, the test series did not indicate a necessity for this practice.

While, the results of this study are promising, additional work is required in order to fully meet the requirements of UFC 3-340-01. The manufacture data states that the shear coupler tested in this study is capable of developing stresses of $1.5f_y$, however, dynamic pull tests need to be performed to determine the ultimate capacity of the coupler and to track the ductility of the reinforcement at high strain rates. In addition, additional in-situ tests need to be performed at higher pressures to verify performance of the coupler at larger rotations. Finally, the test series needs to be expanded to include different coupler types.

In-situ Blast Testing of Shear-Screw Mechanical Couplers

Travis J. Holland
34th DDESB Seminar
13 July 2010

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Mechanical Couplers – Overview (1/2)

- Project Objective
  - Experimental investigation of dynamic response of mechanically coupled rebar under blast loads.
  - Test a specific mechanical coupler, a shear screw coupling sleeve.
- Approach
  - Shock tube test series including concrete slabs with continuous reinforcement, lap splices and mechanical splices.

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Mechanical Couplers – Overview (2/2)

- Traditional approach uses lap splices
  - Requires additional material
  - Results in increased congestion
  - Increases difficulty of concrete placement
- Mechanical couplers offer some benefits
  - No wasted material
  - Reduced congestion
  - Direct transfer of rebar forces

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Requirements for Couplers

- ACI 318-08 *(12.12.3.2)*
  - A full mechanical splice shall develop in tension or compression, as required, at least 1.25(f_y) of the bar.
- UFC 3-340-02 *(4-21.8)*
  - Mechanical devices may be used for end anchorages and splices in reinforcement.
  - These devices must be capable of developing the ultimate tensile strength of the reinforcement without reducing its ductility.
  - Tests showing the adequacy of such devices under dynamic conditions must be performed before these devices are deemed acceptable.

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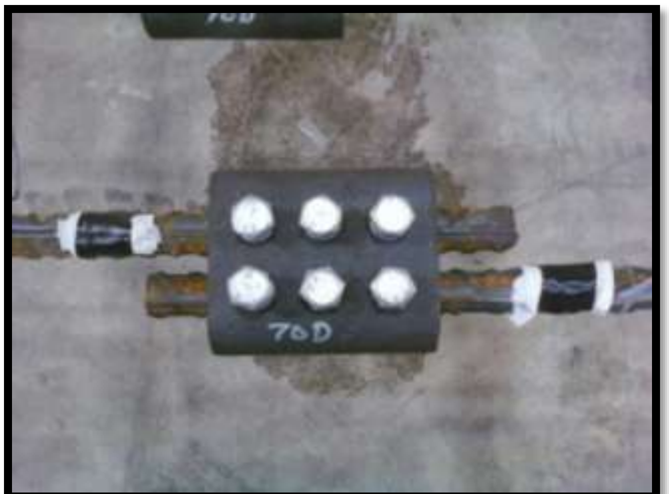
Test Specimen (1/3)

- 8 ft square slab, 5½ inch thick
- Simply supported at top and bottom
- Reinforcing
  - Single layer of steel (no stirrups)
  - Vertical (primary) = #5 bars @ 11¼" spacing
  - Horizontal (secondary) = #4 bars @ 12" spacing
- Materials
  - Concrete f'_c = 4,000 psi nominal
  - Rebar ASTM A 615, f_y = 60 ksi nominal
  - Specific data not available

Test Specimen (2/3)

- Double Barrel Zap Screwlok system by Barsplice Products Inc.
  - Meets ACI requirements for $1.25f_y$ development
  - Capable of developing $1.5f_y$ for a No. 5 bar. (at or above ultimate strength of bar, per UFC requirement)
  - Compatible with ASTM A 615, ASTM A 706 and ASTM A 996 reinforcing bars.

Test Specimen (3/3)

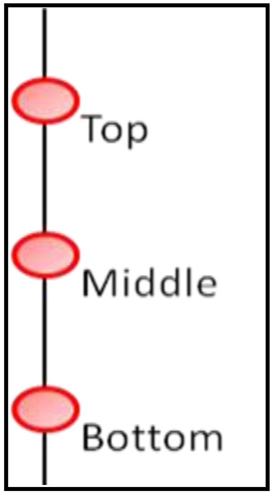


Test Matrix

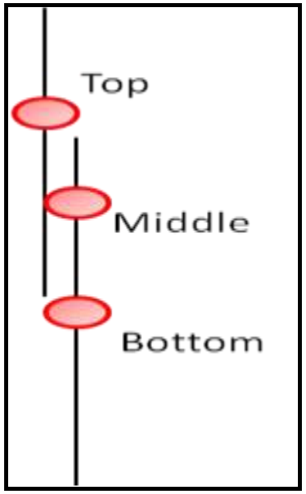
Test No.	Nominal Load		Splice Type	Splice Location
	Pressure (psi)	Impulse (psi-ms)		
1	8	220	None	n/a
2			Lap	Mid-span
3			Mechanical	Mid-span
4	11	310	Mechanical	Third-point
5			Lap	Third-point
6			None	n/a

Strain Gauge Layout (1/3)

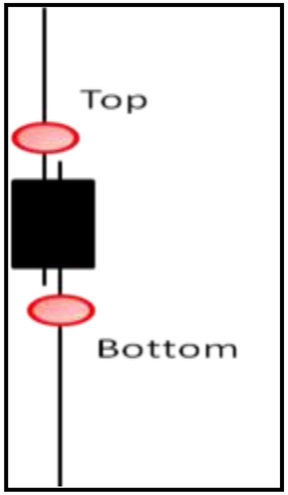
- *Strain Gauges*
  - Locations for strain gauges are selected based on critical areas of a splice or areas of high strain along the reinforcement.
  - Eight strain gauges were utilized for each test.



continuous

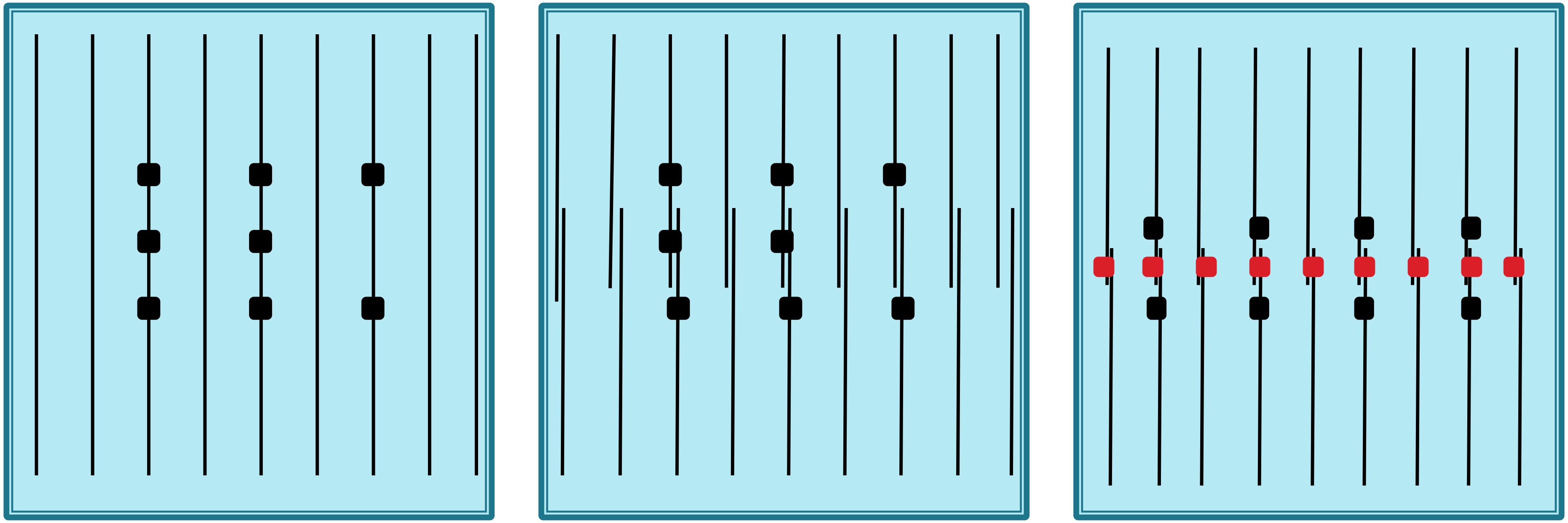


lap



mechanical

Strain Gauge Layout (2/3)

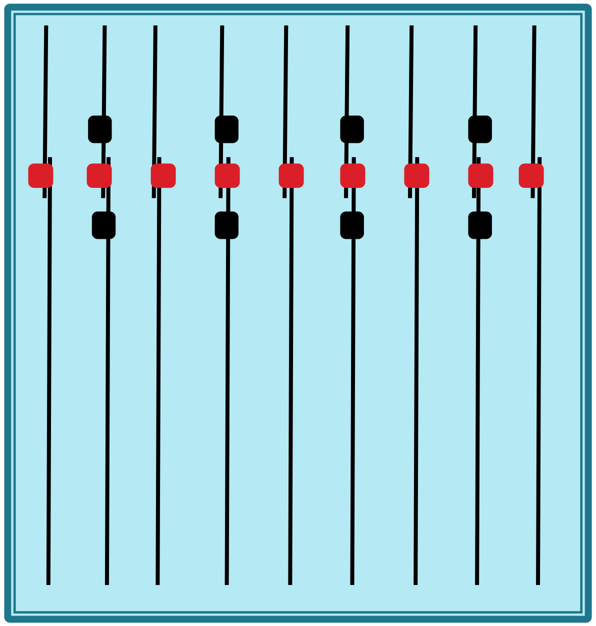


Test 1 – No Splice

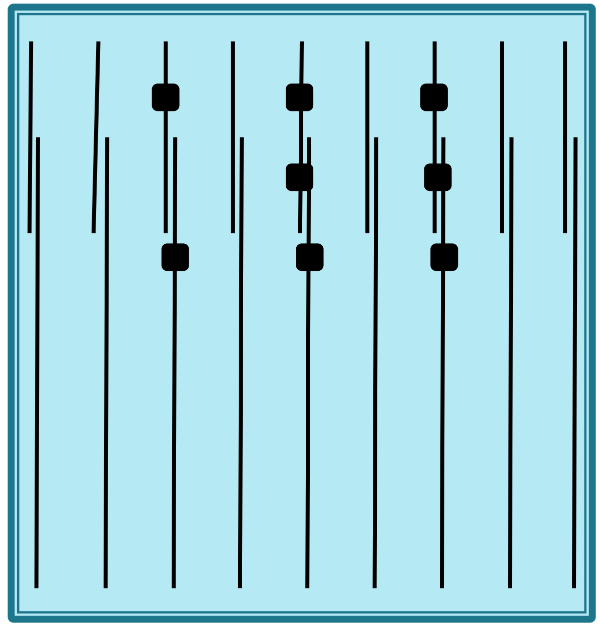
Test 2 – Lap Splice

Test 3 – Mech. Splice

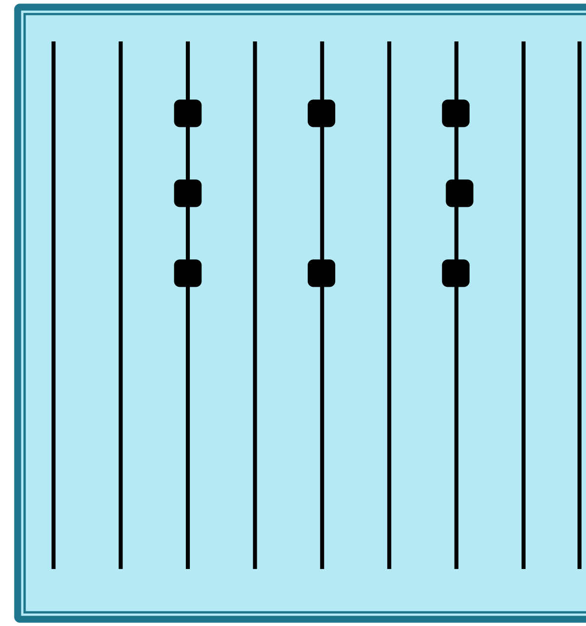
Strain Gauge Layout (3/3)



Test 4 – Mech. Splice



Test 5 – Lap Splice



Test 6 – No Splice

BakerRisk Shock Tube

Wilfred E. Baker Test Facility

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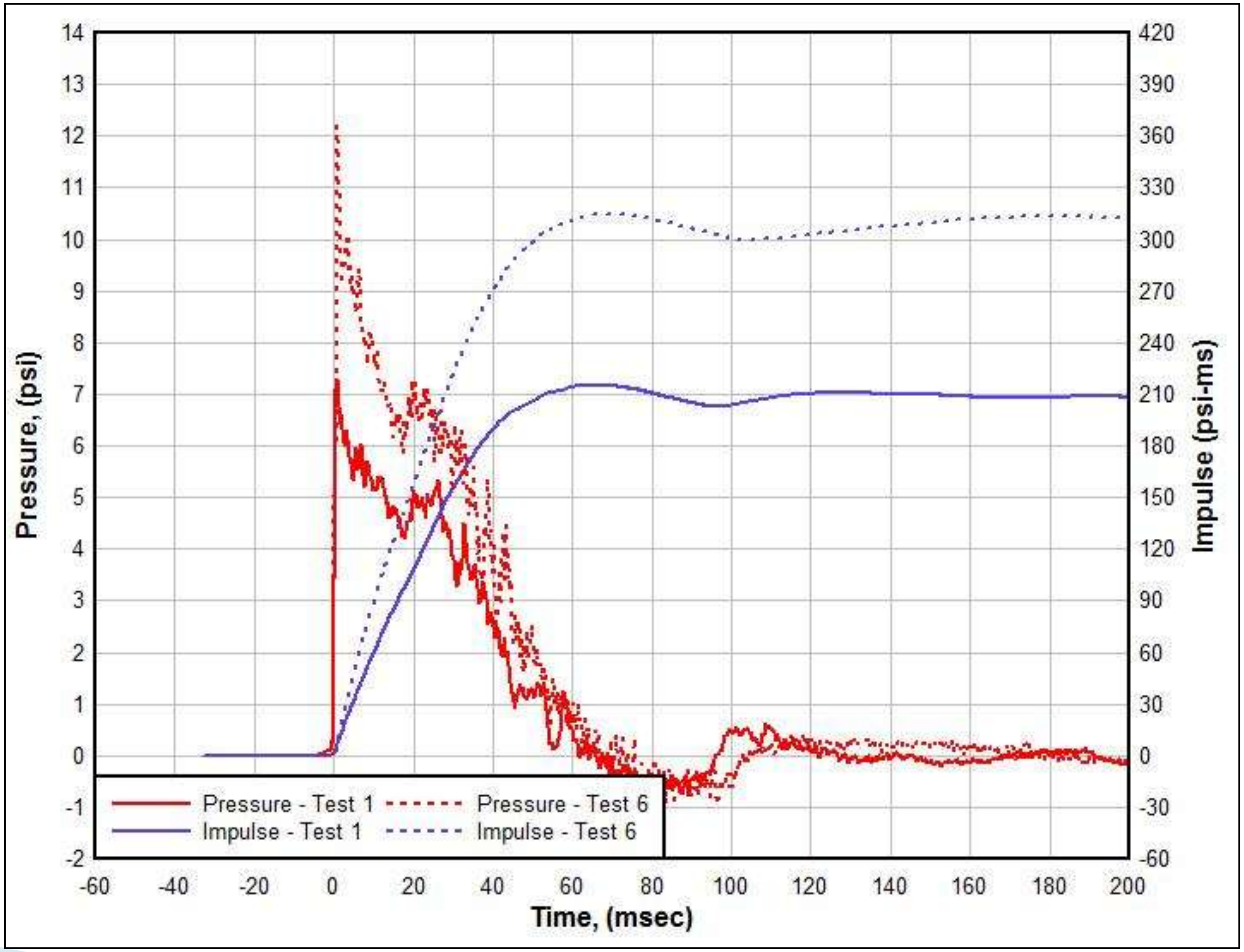
Blast Loads



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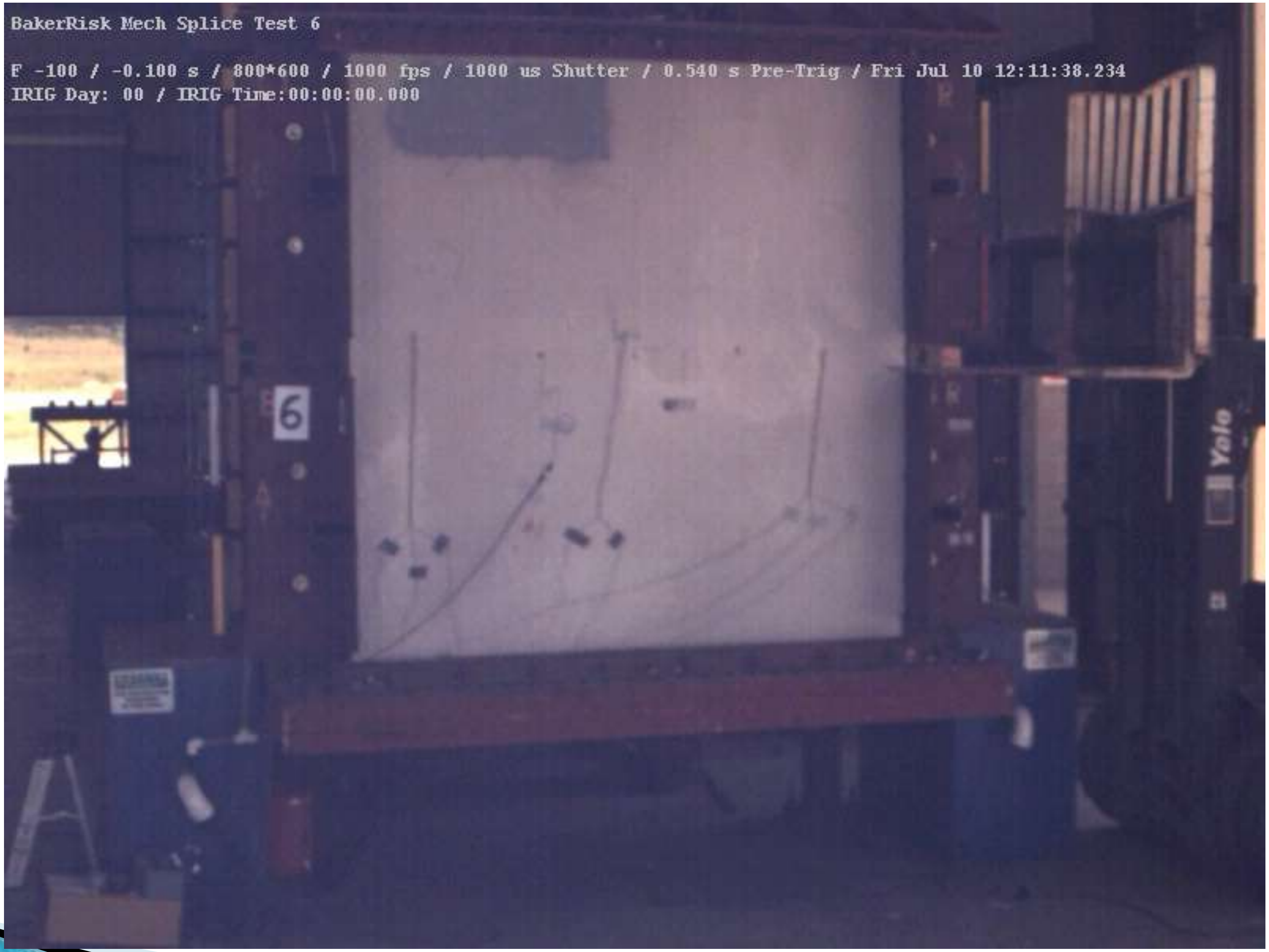
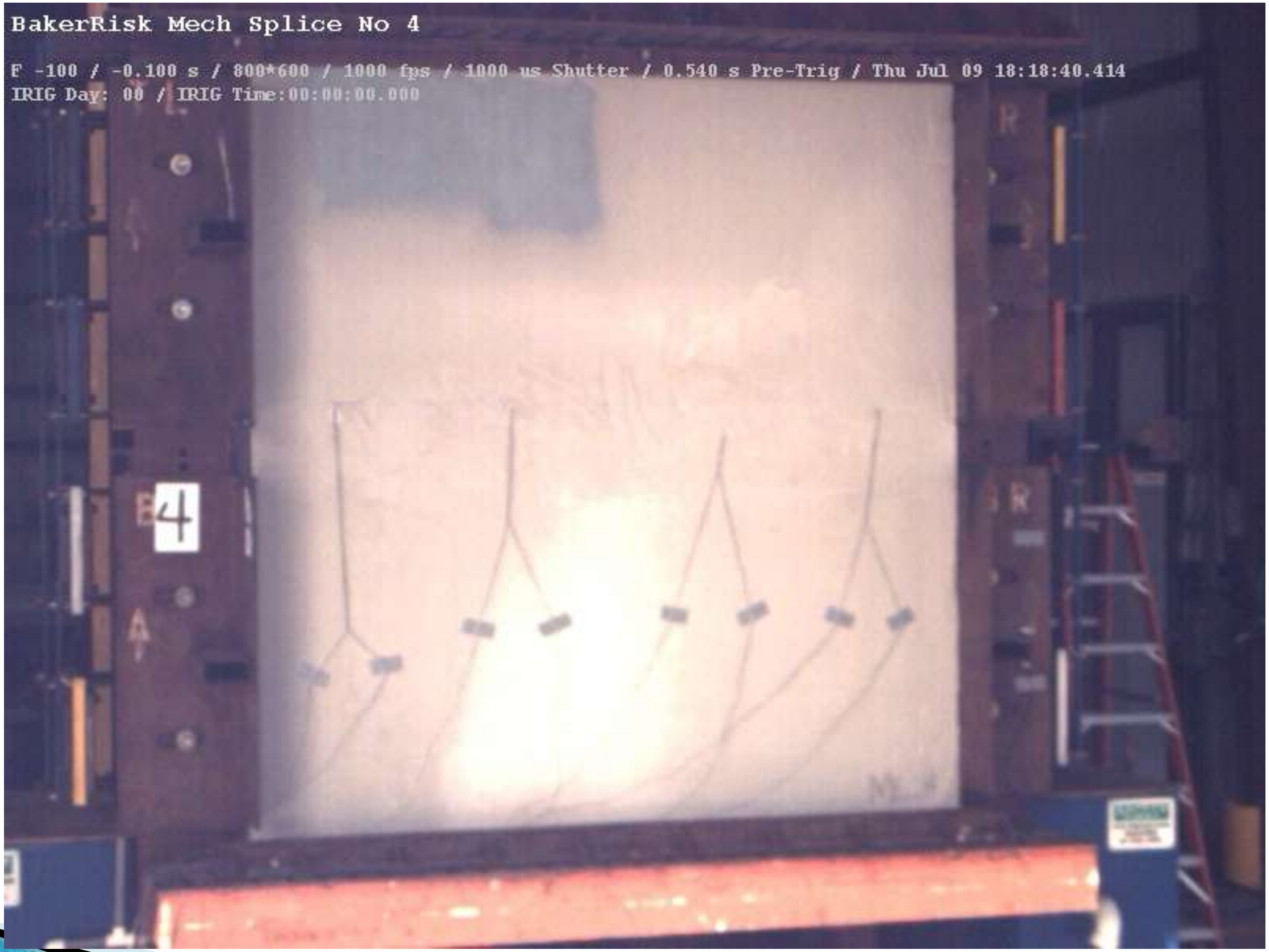
Test 6 Response



Continuous Rebar – 11 psi

Test 4 Response

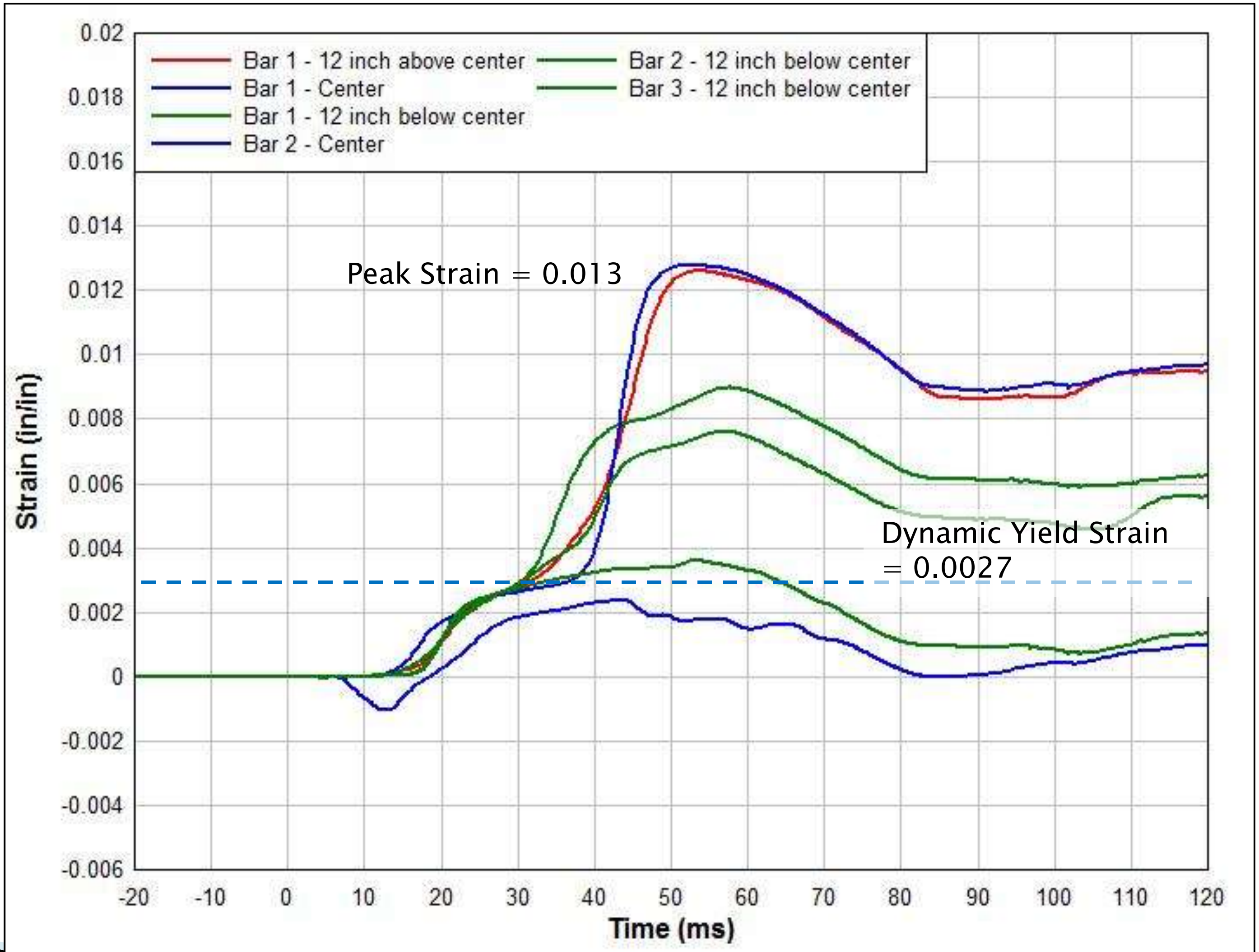


Mechanical Splice at Third-point – 11 psi

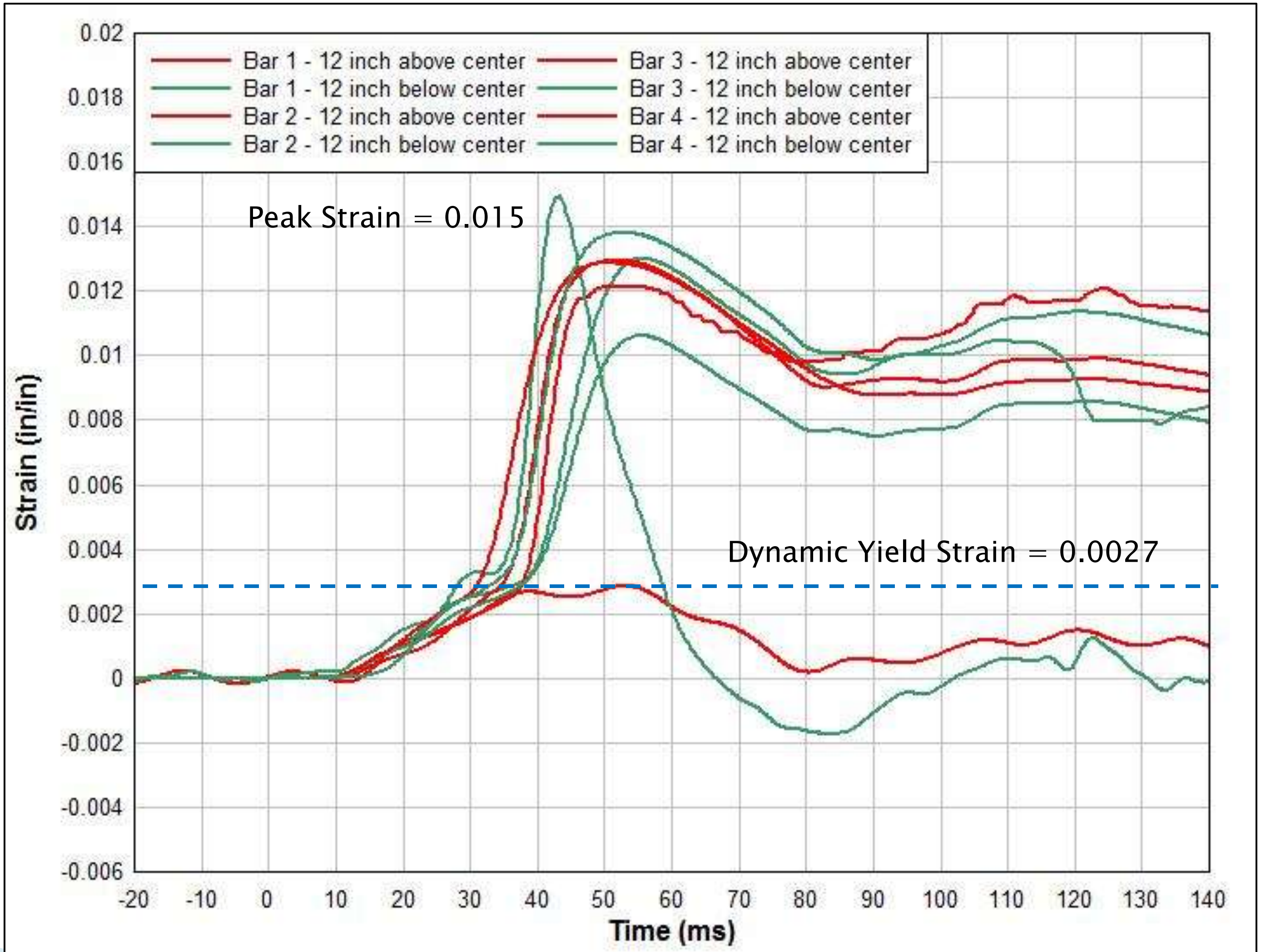
Summary of Peak Deflections

	Test Set	Test No.	Applied Pressure (psi)	Applied Impulse (psi-ms)	Measured Peak Deflection (in)
8 psi load	1	1	7.7	217	2.3
		2	7.6	213	2.3
		3	7.9	221	2.0
11 psi load	2	4	10.7	306	5.5
		5	10.8	311	5.8
		6	10.6	297	6.0

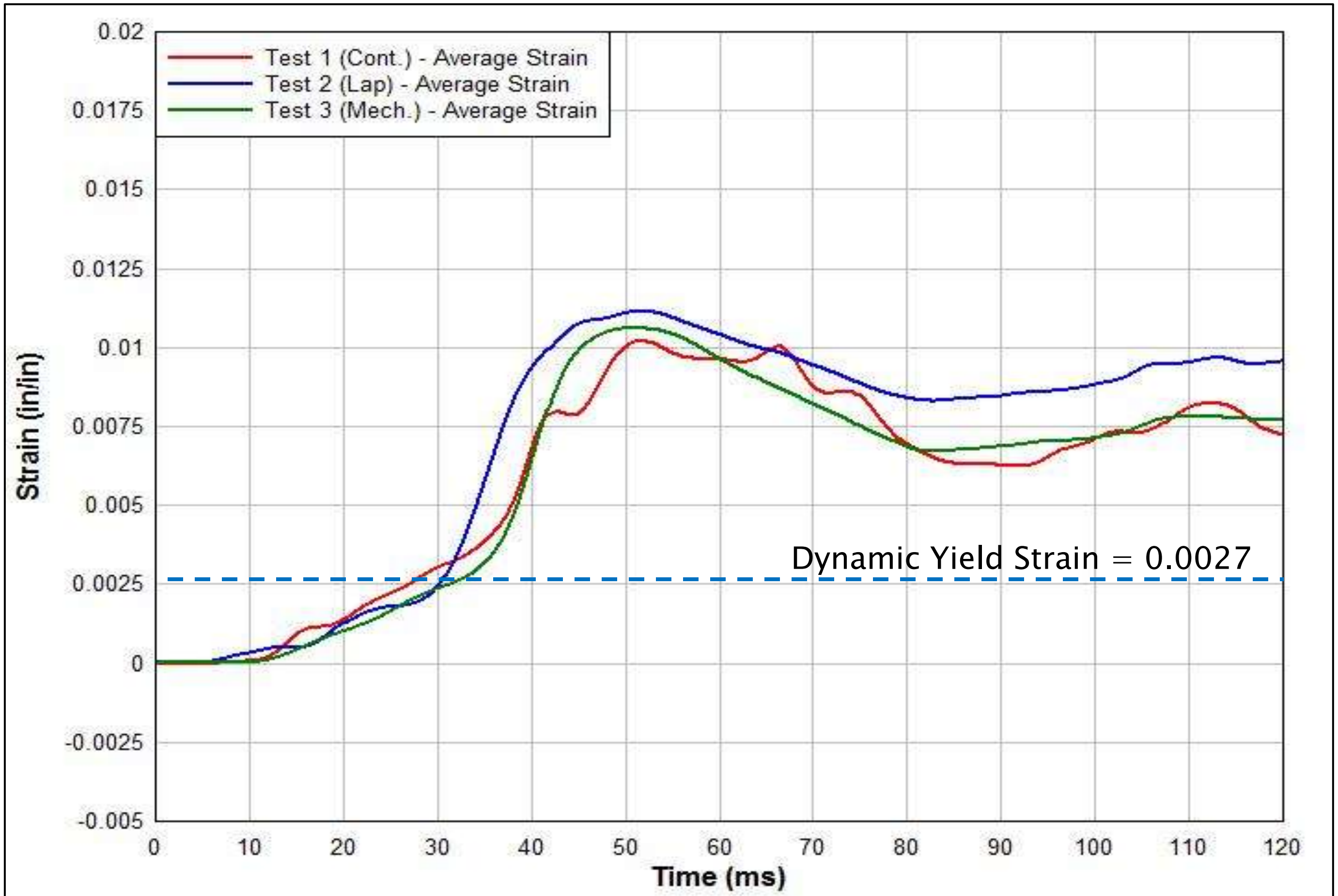
Bar Strain – Test 1



Bar Strain – Test 3



Average Strain – Test 1,2,3



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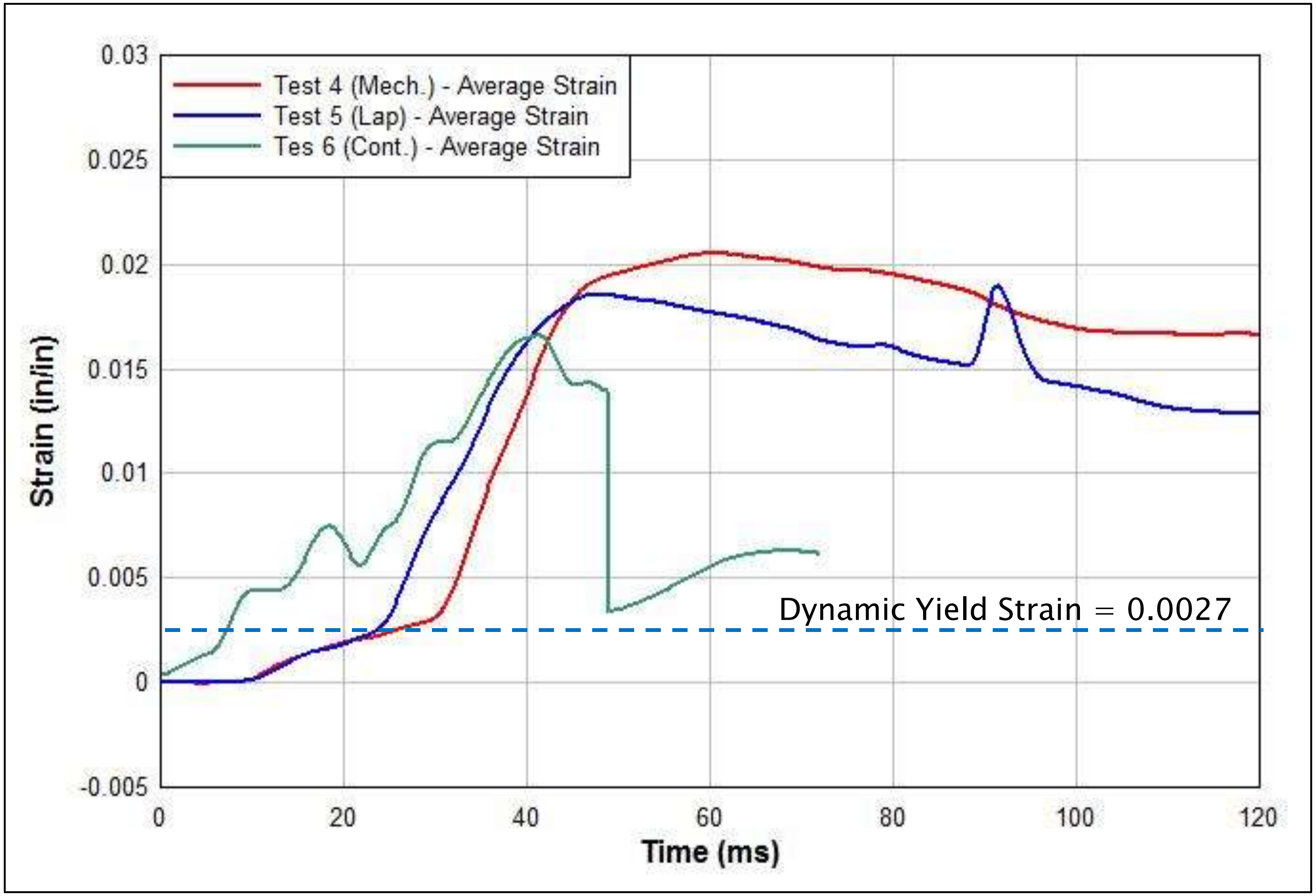
Average Strain – Test 4,5,6



Results (1/2)

- Tests produced consistent data
- Tests exercised slab well beyond elastic limit
  - Rotations exceeding 5 degrees
  - Recording strains up to 3%
- The shear screw couplers are capable of developing the dynamic yield stress of Gr. 60 rebar.
- The couple is capable of developing strains past the yield point without limiting the ductility of the reinforcement.

Results (2/2)

- All three reinforcing conditions produced similar response
  - Mechanical coupler produced ~10% less displacement in both sets of tests
- Tests <u>did not</u> approach ultimate strain values
  - Typically 8–10% for Gr. 60 rebar
- Placing splices away from the peak moment regions of the slab is good practice, however, the test series did not show any necessity for following this practice.

Conclusions

- On track to satisfy 3 out of 3 UFC requirements
  - No reduction in ductility
    - None observed in response regime tested
    - Further testing needed to determine whether full ultimate strain can be reached
  - Capable of developing full ultimate strength of bar
    - Manufacturer testing suggests it can reach (1.5 f_y)
    - Not explicitly confirmed
  - Tested dynamically
    - Tested in realistic slab with realistic loadings
    - Provides additional confirmation in realistic loading conditions

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Future Work

- Perform dynamic pull tests to determine ultimate capacity
- Perform shock tube tests at higher pressures to verify performance at larger rotations/ductilities
- Extend to other coupler types
- Results appear promising

Questions